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Wireless Modes — Part 1

If you employ a wireless data or voice link, you use modes, too!

As you tune around the ham "bands" with a radio or spectrum analyzer, you can hear and see an awful lot of different signal types. Some are whistles, some are warbles or chirps, some sound like vacuum cleaners, and some even sound like voices if you have the right receiver. These different signals are called "modes" by hams — each with its own purpose, strengths, and weaknesses. This column is an overview of fundamental modes used in communication systems. Next time, we'll cover more advanced modes used for data transmission.

RF Signal Basics

All signals — RF or not — are built out of sine waves (even digital signals — a topic for another column). A sine wave has an *amplitude* and a *frequency*. Amplitude is the "size" of the sine wave, and frequency is the number of complete cycles (from zero to maximum to zero to minimum and back to zero) every second, measured in *Hertz* (*Hz*). The time it takes for one cycle is the signal's *period* (*T*), measured in units of time — such as nanoseconds for signals in the GHz range.

Each cycle of the sine wave is divided into 360 degrees — just like the circle. (Radians are another type of angular measurement and a full cycle of a sine wave contains 2π radians.) The position within the cycle is called *phase*, measured in degrees or radians as shown in **Figure 1A**. If two sine waves have the same frequency and begin their cycles at the same time, the signals are *in-phase*. If those same signals begin their cycles at different times, they have a *phase difference* or *phase shift* (**Figure 1B**). If the time difference is one-half cycle so that both signals are zero at the same time but changing in opposite directions, they are *out-of-phase* or *anti-phase* (**Figure 1C**).

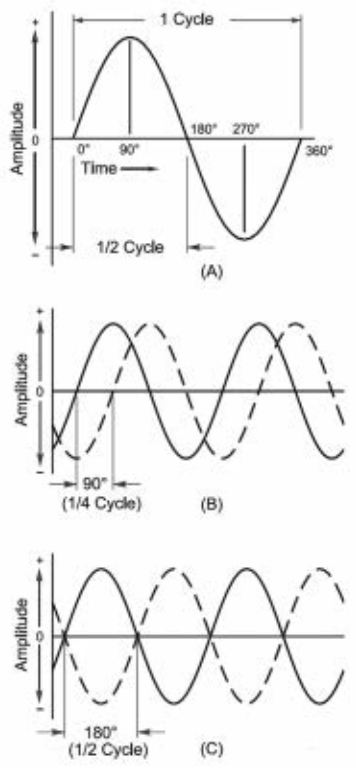

FIGURE 1. Phase is used as a measure of time within the signal. Each cycle of a sine wave is divided into 360 degrees of phase (A). Parts (B) and (C) show two special cases. In (B), the two signals are 90 degrees out of phase, and in (C) they are 180 degrees out of phase or anti-phase. ***(Graphic courtesy of the American Radio Relay League.)***

Sine waves are generally considered to be *RF* or *radio frequency* signals if the wave's frequency is higher than the audio range, which has a maximum frequency of 20-30 kHz. (Some special-purpose communication systems communicate with radio signals at lower frequencies.) The RF spectrum is very broad, extending from just above the audio range to hundreds of GHz. Most wireless systems used by hobbyists range from about 1 MHz to around 10 GHz.

Carrying Information with an RF Signal

By itself, a continuous sine wave doesn't carry any useful information. It's just "there." However, if we vary one of the sine wave characteristics — its amplitude, frequency, or phase — we can use those variations to encode information. This is called *modulation*. Because it's hard to transmit audio or data signals any useful distance by themselves, modulation is used to add them to the RF signal which can be easily transmitted over great distances. When the signal is received, another process can recover the information by decoding the RF signal variations. This is called *demodulation*. (This is where the term *modem* comes from — *mo*dulation-*demo*dulation.)

Because the difference between the information and RF signal frequencies is so great (usually several orders of magnitude), viewing the modulated RF signal on an oscilloscope gives an incomplete picture. To help visualize what happens to an RF signal when it is modulated, engineers display the signal in the *frequency domain* as in **Figure 2**. Amplitude is still on the vertical axis, but now the horizontal axis shows frequency. This is what you would see on a *spectrum analyzer* display. Tuning a

Phase or Polarity?

It is important to distinguish between phase, which represents time or position in a waveform, and polarity, meaning the convention of positive and negative voltage or current. It is quite possible for two signals to have opposite polarities but still be "in phase," for example. Phase in an AC power system refers to one of the distinct voltage waveforms generated by the utility.

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www.nutsvolts.com/magazine/article/March2017_HamsWirelessWorkbench_Wireless-Modes.

receiver can be imagined as sliding its receive window back and forth along the horizontal axis. The receiver will hear and attempt to demodulate any signal in the window.

That steady sine wave can be represented as a single vertical line as in **Figure 2A** — this *unmodulated* signal has a single frequency (f) and a constant amplitude. The information to be added to a signal generally has a more complicated spectrum.

For example, the spectrum in **Figure 2B** is typical of human speech: many individual frequency components ranging from strong ones with higher amplitudes around 300 Hz, then tapering off around 3 kHz. We could draw a vertical line as in **Figure 2A** for every different component in a speech signal, but it is a lot easier to draw a shape that represents the spectrum of speech. Different types of information (data, music, speech, telephone dialing tones, etc.) have spectra with different shapes.

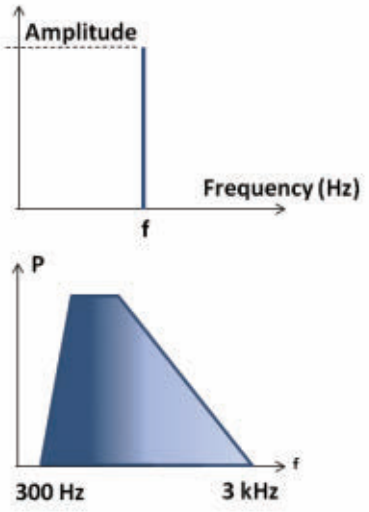

FIGURE 2. The spectrum of a single sine wave (A) has only one component, shown as a vertical line at one frequency (f) and with a fixed amplitude. The spectrum of a typical speech waveform (B) consists of many component signals with different frequencies and amplitudes. Most communication systems consider speech to extend from 300 to 3,000 Hz.

Modes = Information + Modulation + Protocol

It is not enough to simply add information onto an RF signal and transmit it. The receiving station (even a little Arduino wireless data shield can be considered a "station") has to know what frequency range to listen on, what kind of modulation is being used, the type of information being sent, and how it is encoded. This defines the *air link* which defines the signal you would observe on the air.

Once the air link characteristics are determined, the receiver also has to understand the *protocol* being used — the "rules of engagement" for establishing contact (a *session* in datacomm-speak) and managing the flow of information. Finally, the receiver has to be set up to recover the information and present it to the user in an appropriate format. It wouldn't do for a receiver to recover 1s and 0s representing an MP3 file but send them to the speaker as a series of pops and clicks!

All three parts — the type of information being transferred, the air link that gets the information from point A to point B, and the protocol that manages the transfer — create what hams call a *mode* and what the FCC (Federal Communications Commission) refers to as an *emission*.

For example, if I want to send a text file via ham radio using the Winlink system (**www.winlink.org** — pretty cool, huh?) on the shortwave bands, I would use a mode consisting of the PACTOR protocol and AFSK (audio frequency-shift keying) to modulate my voice transmitter. Text characters + PACTOR + AFSK form one of the many permitted modes used by amateurs.

In my living room, I might use a different mode consisting of digitized audio + Bluetooth which specifies GMSK modulation to stream music to my wireless headphones.

Hopefully, you now get the idea of combining data with a protocol with a way of modulating an RF signal. Let's take a look at the modes used by hams.

On-Off Keying (OOK) or "CW"

The very oldest mode of wireless transmission is the simplest, consisting of just turning a transmitter on and off in a coded pattern that represents characters. (Turning a transmitter on is called "keying" whether a telegraph key is used or not.) The coded pattern used by nearly all hams is Morse code and it has been around since 1840 in several varieties (**en.wikipedia.org/wiki/Morse_code**). The first was American Morse, then the Continental Code was created. Finally, today's International Morse was defined by the ITU and is still in use today — it's actually quite popular (see the companion article in this issue by John Thompson on CW making a comeback).

What does "CW" — standing for the old term "continuous wave" used for Morse code transmissions such as in **Figure 3** — "look like" to a spectrum analyzer or a tunable receiver? Going back to **Figure 2A**, you would "see" a vertical line appearing and disappearing in the

FCC Emission Designators

In order to write precise rules for users of the RF spectrum, the FCC has to use equally precise definitions of what those signals are. Those definitions are called emission designators. Each designator consists of a sequence of characters that define bandwidth, modulation, nature of the signal, and the type of information. For example, AM broadcast signals with the full 10 kHz audio bandwidth have the designator 20K00A3EGN. You can find out all you ever wanted to know about emission designators at **www.comsearch.com/articles/emission.pdf**. There are an amazing number of signal types "out there!"

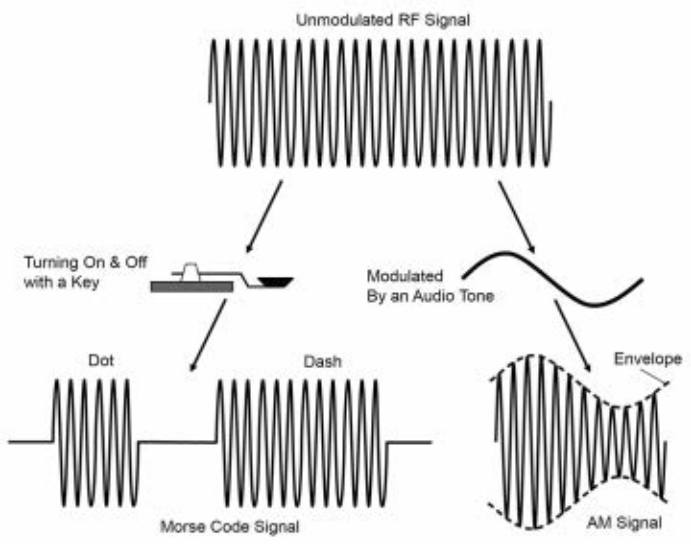

FIGURE 3. On-Off Keying (OOK) of an unmodulated carrier signal in a pattern such as Morse code is a very simple form of amplitude modulation (AM). A tone or speech can also be used to modulate the signal, resulting in a signal whose shape or envelope contains the information from the tone or speech. ***(Graphic courtesy of the American Radio Relay League.)***

pattern of Morse code. The characteristic "beeping" comes from circuitry in a CW receiver that converts the presence of the signal into an audio tone. No signal, no tone. It's very simple and easy to learn.

Amplitude Modulation or AM

The next oldest mode is *amplitude modulation* or *AM*. (Hams sometimes jokingly call AM "ancient modulation.") OOK is a simple form of AM in which the amplitude is either zero or non-zero, but to send speech or music something more capable is required. The simplest way of creating an AM signal is to first create an unmodulated RF signal called a *carrier*. Next, make its amplitude larger and smaller in the same way a speech waveform gets louder and quieter.

Figure 3 shows the result if a single audio tone is used as the *modulating signal*. The resulting AM signal can be transmitted over the air and any receiver that can follow the signal's outline — called the *envelope* — can reproduce the original speech or music. It's surprisingly easy. Check out the many crystal radio receiver designs at **www.midnightscience.net**.

On our spectrum analyzer display, however, the simple vertical line of the original RF signal has suddenly become quite a bit more complicated. The AM signal now consists of the steady RF carrier flanked by symmetrical signals on either side (called *sidebands*) as shown in **Figure 4**. This combination of a carrier and sidebands is called a *composite signal* — one with several components.

Figure 4A shows what happens for modulation by a single tone. A sideband is created above (the *upper sideband* or *USB*) and below (the *lower sideband* or *LSB*) the carrier. The frequency of the sideband differs from the carrier by the frequency of the tone. If the tone is a 1,000 Hz tone and the carrier's frequency is 1 MHz, the sidebands would be found at 1.001 and 0.999 MHz.

If speech was used to modulate the carrier, the situation of **Figure 4B** would result. The speech would be translated into sidebands with the same bandwidth as the speech itself: one above and one below the carrier. What's particularly important to note is the sidebands are mirror images of each other. The USB still has low speech components below the higher components, but the LSB is inverted. In both cases, the individual speech components are symmetric about the carrier.

Single Sideband or SSB

Why does AM need two sidebands with the speech information? What does the carrier do? The answers are "it doesn't" and "nothing!" AM is easy to generate and receivers are simple, but the cost is low efficiency. Fully one-half of an AM signal's power remains in the carrier, which actually carries no information. The modulating information is duplicated in the sidebands, as well. Only one-fourth of the AM signal's power goes into a unique signal — one of the sidebands.

During the 1930s, research showed that there were several ways of removing or *suppressing* the carrier and one of the sidebands. Either of the remaining sidebands carried all of the information, but the receiver had to supply the missing carrier — which turns out to provide a frequency and phase reference for demodulating the sideband.

Advances in receiver design during and after WWII made SSB practical, and it soon replaced AM for most point-to-point communication uses. By putting all of the power into one sideband, the effect on the signal-to-noise ratio (SNR) was a four-fold (or 6 dB) improvement. Either smaller transmitters could be used for equivalent range or the same power could double the signal's range.

Either LSB or USB can be used, and both are common today in amateur radio, marine radio, aviation, and

That Warm AM Sound

AM broadcast signals were once the highest of hi-fi, and many homes sported a large console tube-type receiver with large speakers. Ball games, musical programs, and live announcers really do sound great on this equipment! Many amateurs enjoy keeping their "big iron" rigs on the air for the warmth of the AM audio with its better bass response and relaxed style of operating. AM will be around a long time — both broadcast and ham.

government communications. Because of the mirror image sidebands, the receiver has to be set to receive the correct sideband — LSB or USB — or the demodulated information will be garbled. Certain transceiver design choices made decades ago led to the convention of using LSB below and USB above 9 MHz, but functionally they are equivalent.

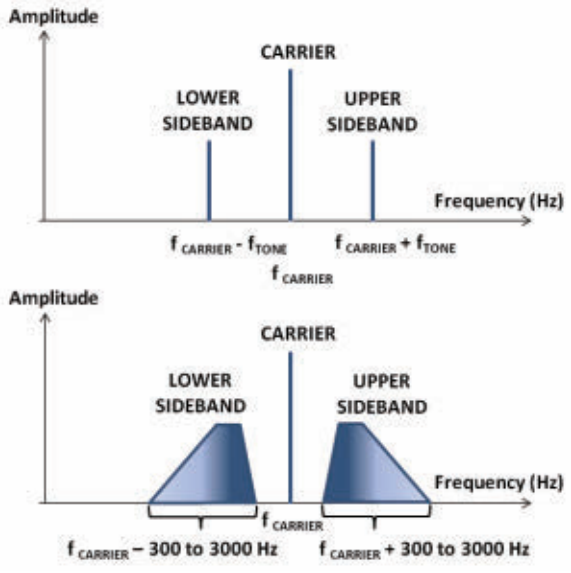

FIGURE 4. The spectrum of an AM signal modulated by a single tone (A) shows the carrier and two sidebands, separated from the carrier by the frequency of the modulating tone. The spectrum of an AM signal modulated by complex information such as speech is shown at (B).

Frequency Modulation (FM) and Phase Modulation (PM)

Like amplitude, both frequency and phase can be modulated to add information to an RF carrier signal. FM or PM is created by varying the value of a resonant circuit's capacitor (FM) or the reactance of a phase-shifting capacitor (PM). Frequency and phase are closely related mathematically and so are FM and PM. An unmodulated RF sine wave is described by A sin (ϕ, where the sine wave's amplitude is A and its angle is $\phi = 2\ \pi ft$. AM varies A, and both FM and PM vary ϕ. As a result, FM and PM are called *angle modulation*.

Changing a signal's frequency or phase is equivalent so FM and PM are almost the same. The main difference between FM and PM is that phase modulation accentuates the higher frequencies of the modulating signals — an effect called *pre-emphasis* — as if a high-pass

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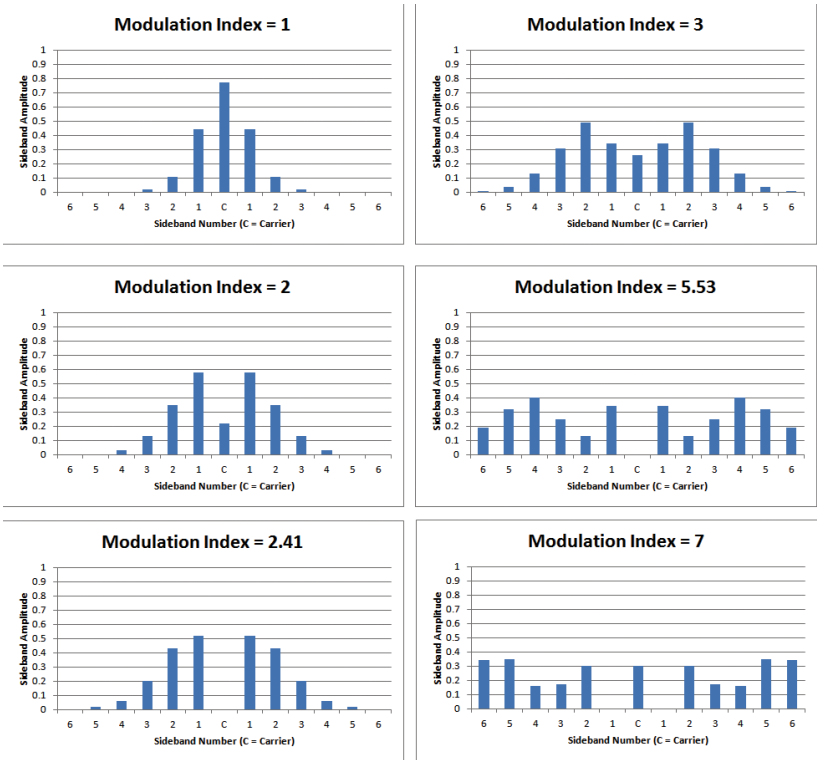

FIGURE 5. The spectrum of FM signals is very complex, depending on both the modulating signal's frequency and amplitude which control the signal's modulation index. At some values for the index (such as 2.4), the carrier disappears. There are an infinite number of sidebands, but the FM signal's power is constant.

filter was acting on the audio. To restore a "flat" frequency response, complementary *de-emphasis networks* (a low-pass filter) had to be used in the receiver.

The spectrum of FM/PM signals is much more complex than AM and SSB signals. (I'll just use FM to refer to both FM and PM from here on.) As with AM, there is a single carrier signal. However, to create a signal with a frequency (or phase) that varies with a modulating signal, essentially an infinite number of sidebands are required! (The mathematical expression that defines the spectrum is called a *Bessel function*.) The amplitudes of the carrier and all the sideband components are controlled by the modulating signal's amplitude which determines the signal's *modulation index*.

Figure 5 shows FM signals modulated by a single tone at different modulation indexes. You can see bandwidth increasing with the modulation index. The power in an FM signal is divided up between the carrier and all of the sidebands so that the total power is always the same — FM is a *constant power* signal. When an FM transmitter is keyed, the output power is the same whether you are speaking or not. Note that for some values of the modulation index (such as 2.4), the carrier can even be zero.

Narrowband FM (NBFM) signals have a modulation index less than or equal to one. It is used where power efficiency is more important than fidelity, such as for handheld FM transceivers. *Wideband FM (WBFM)* signals — such as for high-fidelity commercial FM broadcast — have a modulation index of 10 or more, and occupy up to 150 kHz of bandwidth.

Why go to all the trouble of FM and PM and those complicated signals? Originally, all voice-carrying radio signals were AM. As anyone who has listened to AM radio knows, static can be a real problem. It's an AM signal just like the one you're trying to listen to, so the radio "demodulates" its crashes and buzzes, too. An FM receiver, though, only responds to variations in signal frequency, not amplitude. So, it can almost completely reject AM static and noise. As a result, a strong FM signal has almost no noise — even in the middle of stormy weather.

As an additional benefit, FM's constant power nature means that amplifiers for the RF signal don't have to be linear so they can reproduce the signal's envelope. That means the amplifiers are simpler, require far fewer adjustments, and can be much more efficient than linear amplifiers for AM or SSB signals.

Data Signals Next Time

If you want more information about AM, FM, and SSB, check the ARRL's Radio Technology Portal's (**www.arrl.org/tech-portal**) Radio Technology Topics section. The Agilent company has also published a detailed application note about spectrum analysis of AM and FM as well, that's available at **cp.literature.agilent.com/litweb/pdf/5954-9130.pdf**. There's more than enough to keep you busy until the next column comes along!

While digital data can be sent over AM or FM systems, it's more effective to use modes designed specifically for data. In a future Ham's Wireless Workbench, we'll start with a simple two-tone frequency-shift keying (FSK) signal and work our way up! NV

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Wireless Modes – Part 2

More modes, baby! Live listening, too!

Ham Radio Data Modes

The original modes used by hams were intended for "human copy" in that the information was meant to be understood by a human listening to the receiver's audio output. Even the initial "spark" (imagine turning a Tesla coil on and off with a Morse code key and you get the idea) was received by ear. The spark was "chopped" by a rotating wheel with contacts on it. Turning the spark on and off at a rate in the low audio range (less than 1,000 Hz) made the hiss of the radio spark audible as a tone.

In the Shack

Spark transmitters used high voltage arcs which were not only dangerous, but made one heckuva racket. The noise, fire hazard, and smells of ozone and various burning things (sounds like fun, doesn't it?) caused the transmitter to be frequently banished to a backyard garage or shed for safety and sanity.

This resulted in the term "radio shack" which is still the slang today for a ham's station — no matter how neat and tidy. Yes, that's where the store's name came from!

Human copy was the norm as CW (from "continuous wave") displaced spark. Then, the voice modes of AM, FM, and SSB (see the previous column) were introduced. Most ham radio is conducted by one of these modes even today. However, the times, they are a-changin'.

Digital modes — according to the Federal Communications Commission (FCC) — are those that exchange information as characters. More accurately, the FCC distinguishes between *data modes* and *radioteletype*, or *RTTY* (pronounced "ritty" by hams; see **en.wikipedia.org/wiki/Radioteletype**). In data modes, characters are exchanged by computers (including microprocessors or other digital gadgets) and might represent a file, a message, telemetry, command characters, or something similar. RTTY, on the other hand, is a special data mode — the original!

RTTY, Our Digital Ancestor

RTTY is formally defined as *direct-printing telegraphy* because of its origins as an electro-mechanical system that connected keyboard-like contraptions over a telephone line or radio link. The bits of each character are encoded as a pair of tones for transmission. The receiver audio is then turned into printed characters by the *teleprinter*. (There's more to it, but a complete explanation would take at least one whole article!) Teletype — now a generic term for the mode — was actually the name of the Teletype Corporation (**en.wikipedia.org/wiki/Teletype_Corporation**).

The first working teleprinter was developed in 1908, but the radioteletype system really came into wide use in the 1930s. Without making this in to too much of a history lesson, the Teletype Model 15 was the PC of its day. Its maze of solenoids and levers was the pre-electronic equivalent of a UART and terminal. If you've ever seen one running, it's unforgettable. "How the Teleprinter Works" is a 1940 tutorial about these mechanical marvels (**www.youtube.com/watch?v=HcMHam54EOI**) and a video of a working Model 15 that was in service for more than 50 years can be seen online at **www.youtube.com/watch?v=Ml00ngVwrcU**. There is something very cool about watching a teleprinter over the Internet!

Many terms used in digital communications today — baud, mark, and space are just a few — came from the world of radioteletype. *Baud* (the number of symbols transmitted per second) is named for Baudot, who invented the five-bit code used to encode characters. *Mark* and *space* refer to the bits of the code. *Start* and *stop* were the synchronization intervals between characters, and so forth.

RTTY was the direct precursor to all of today's digital communications and many veteran programmers used teleprinters — particularly the Model ASR 33 — to communicate with mainframes "back in the day." Hams adapted surplus teleprinters to deploy amateur radio's first digital mode in the post-WWII era. The mechanical units were eventually replaced with electronic display terminals, then microprocessor based systems, and finally the PC and sound card to send and receive the world's oldest digital mode.

RTTY may not be the most robust in terms of error rate and it's certainly not the fastest, but it's simple and easy. Anyone can listen into the conversation and it doesn't require special or proprietary equipment. RTTY is closing in

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on its first century and it will probably be around for quite a few more years.

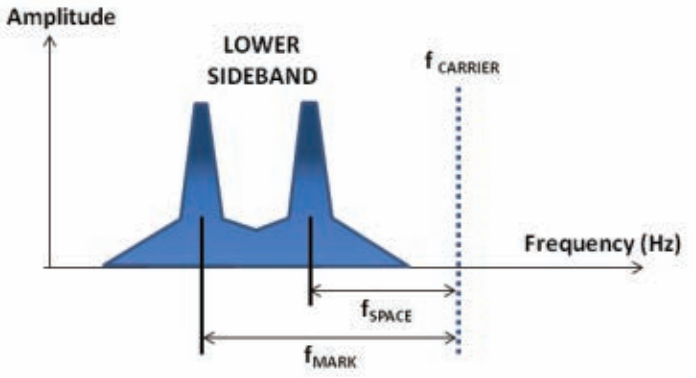
Frequency-Shift Keying (FSK)

The two tones used by RTTY are a type of modulation known as *frequency-shift keying* or FSK (**en.wikipedia.org/wiki/Frequency-shift_keying**). In FSK, shifts in frequency are the *signaling event* and the period during which a tone is transmitted is the *symbol*. There are several common methods of modulating a carrier to create FSK:

1. Shifting the frequency of an RF oscillator back and forth.
2. Modulating an SSB transmitter with tones instead of speech.
3. Modulating an FM transmitter with tones instead of speech.

On the air, methods 1 and 2 sound exactly the same. An unmodulated carrier and a sideband created by a single tone are identical signals. Method 3 creates a standard many-sidebands FM signal, but the audio output from the receiver sounds the same as the audio from methods 1 and 2.

Method 1 is called *direct FSK* because the RF carrier frequency is controlled directly by the digital data signal input to the transmitter. Methods 2 and 3 are called *audio frequency-shift keying* or AFSK because the digital signal is used to create an audio signal (the tones) that modulates the transmitter. The end result of all three is a set of tones that represent the 1/0 of a digital signal.



■ **FIGURE 1.** A typical ham radio RTTY signal spectrum for an AFSK signal. The transmitter is set to LSB and audio tones with f_{MARK} and f_{SPACE} are input in place of microphone speech. A receiver set to LSB and tuned to the same carrier frequency would recover the audio tones with the same mark and space frequencies.

RTTY uses a pair of tones (mark and space, mentioned earlier), so it is *binary FSK*. The difference between the two tones is called the *shift*. Most ham radio RTTY on the HF bands (shortwave frequencies below 30 MHz) has a 170 Hz shift. On the VHF and UHF bands, hams use AFSK over an FM link with a 1,000 Hz shift between the tones. You can hear a sample of what FSK/AFSK signals sound like online; see the **sidebar**, "Tuning In to Digital Modes." **Figure 1** shows a typical AFSK RTTY signal on the HF bands using lower sideband by convention. Note that the spectrum has to "spread out" due to the extra sidebands created by the rapid switching between tones.

Two-tone binary FSK is the simplest form, but more tones can be used now that we have more processing power to throw at the problem. By using more tones, the encoding can be more sophisticated to overcome noise, distortion, and interference from other signals. Amateurs use *multi-tone FSK* or MFSK with the number of tones ranging from four to more than a dozen. The most common on the HF bands are Olivia, ALE, MFSK8 and 16, and JT9 and 65. On the VHF and higher frequencies, MFSK441 is used to communicate via ionized meteor trails, and JT65 is used to bounce signals off the Moon!

The Radio Channel

It's worth mentioning at this point why having all these modes is useful. The radio channel — the physical over-the-air portion of the signal's journey — is quite a bit different than one composed of wires. Fading, noise, reflections, and a multitude of other things affect the radio signal in ways that confuse the demodulators and decoders. Different frequency ranges have different characteristics as well,

Breaker, Breaker

Have you ever wondered where the term "break" came from? It is one of the oldest communications terms still in use (along with packet and checksum), with its roots in the early 1840's landline telegraph system.

Those early systems were constructed "party-line style" with the wires connecting one station to another through a sounder. Having all stations "in series" meant that they all heard all of the traffic on the line. The wire also ran through a telegraph key, and closing the key allowed the current to flow through wire. If a station wasn't transmitting, it was expected to close the key — that's what the shorting bar is for on a telegraph key.

So, what if a station needed to jump into the ongoing traffic with an important message, like the bank was being robbed? The operator would remove or open the shorting bar to break the current path, and all stations would hear the line suddenly go dead. The sending operator would wait long enough that every other operator was paying attention, then send the message. This is "breaking in" and on voice circuits, the operator would wait for a pause, then say "break!"

Now you know "who's the breaker?"

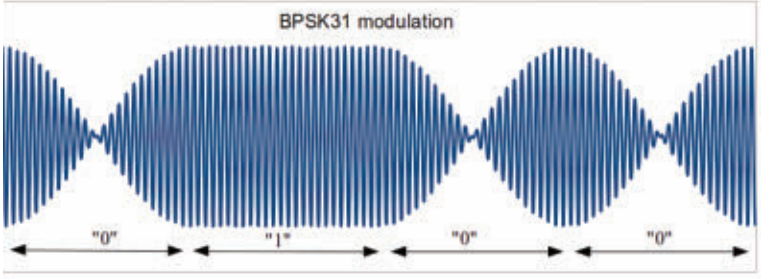
A Nobel Effort

As teenage ham radio experimenters, Joe Taylor K1JT and his brother Hal K2PT enjoyed operating on the VHF bands, using a type of propagation called "scatter." Joe parlayed that early interest into a Nobel Prize in physics — he and Russell Hulse discovered binary pulsars which provided the first evidence of gravitational radiation, detected directly just last year. More recently, Joe decided to apply some of his weak-signal expertise in amateur radio, resulting in the set of WSJT modes (for Weak Signal Joe Taylor). These techniques have opened up numerous vistas for hams, enabling many to explore "moonbounce" with modest equipment; use the ionized trails of meteors as radio reflectors; and communicate at signal strengths far below the noise.

His software is freely available (**www.physics.princeton.edu/pulsar/K1JT**) and can be used by non-hams to listen in. Why not join the fun and see where it might lead you?

with the lower HF ranges different than the upper with those both different than VHF/UHF, and microwave is different still. Whether the stations are stationary or moving also affects the signal. For each type of environment and application, mode designers have selected different combinations of modulation, encoding, and protocol to work effectively.

While it might be understandable to view this much variation as an obstacle, amateurs view it as an opportunity! Starting in the mid-1990s, the FCC stopped trying to evaluate and approve each new mode for the hams. The rule became — within certain limits of bandwidths and broad types of modulation, as long as the mode's design is made public — it is legal for hams to try. And try they have with dozens of different modes and variations heard on the amateur bands every day. More are being developed all the time and with software-defined radio (SDR) technology becoming widely available, I expect many more modes to be invented. If this sounds interesting to you, ham radio is a perfect place to apply your talents!



■ **FIGURE 2.** This waveform of a PSK31's audio shows the phase reversal that occurs between the 1 and 0 periods of the signal. (*Graphic courtesy of Albany45 at* **wikipedia.org**.)

Phase-Shift Keying (PSK)

A closely related type of modulation is *phase-shift keying* or PSK in which the phase of a signal is compared to a reference and varied to encode the digital bits. (The clever reader may have also realized that Morse code is a kind of *amplitude-shift keying*, extending the "shift" metaphor to all three of the signal parameters: frequency, phase, and amplitude.) The reference can be a separate signal, but for efficiency the usual method is to simply vary the signal phase and let the receiver's circuits detect the *change* in phase. This is called *differential PSK*.

Like FSK, there are various schemes that get more and more complex. The simplest type of PSK is *binary PSK* or BPSK in which the phase shift is 180°. Once a reference phase is established, the received signal is either in-phase or out-of-phase. BPSK is sometimes called *phase-reversal keying* for that reason. **Figure 2** shows a BPSK waveform changing from the phase representing a logic 1 to the phase representing logic 0 and then back again.

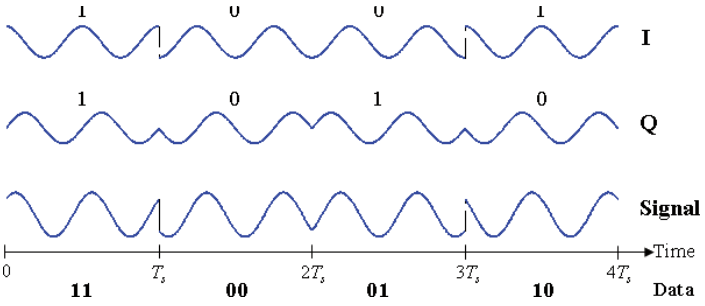
BPSK is the most popular of the new digital modes used by hams where it is known as PSK31 (**en.wikipedia.org/wiki/PSK31**). The 31 stands for the mode's baud (remember that "baud" means "symbol rate" so "baud rate" is redundant) which sounds awfully slow, but that's about normal typing speed. PSK31 is perfect for keyboard-to-keyboard chatting. Furthermore, the bandwidth required for PSK31 signals is only 50 Hz, so lots and lots of signals can share the limited ham bands — an important part of using the spectrum wisely (and getting along).

PSK31's efficient use of bandwidth also makes it an efficient user of power, requiring only a few watts of RF output to communicate worldwide when the bands are open. PSK63 that sends bits twice as fast (and consumes twice the bandwidth) is also popular. In recordings of PSK31 signals, the buzzing you hear superimposed on the steady tone is created by the audio waveform's phase reversals.

PSK31 also uses a special code for the characters it exchanges. *Varicode* (**en.wikipedia.org/wiki/Varicode**) is an abbreviation of "variable-length code." Where ASCII and Baudot use the same number of bits for each character (seven or eight for ASCII and five for Baudot), Varicode uses different numbers of bits for different characters. Like Morse, Varicode uses short sequences for the most common characters (E is one dit in Morse and 1110111 in Varicode) to save time. There are more variable-length codes; the design of codes, in general, has a long history in both mathematics and espionage.

Quadrature or I/Q Modes

As with FSK, there's no reason to only use two



■ **FIGURE 3.** QPSK is created from two independent carriers with the same frequency, but a 90° phase shift. The carriers are modulated by the digital signals, then recombined to make the output signal. (*Graphic courtesy of Splash at* **wikipedia.org**.)

values of phase shift (none or 180°), and there are many versions of phase- and amplitude-shift keying systems that use more intermediate values. The most common are called *quadrature* modulation because they are created by modulating a pair of carriers that have the same frequency, but have a 90° phase difference. One carrier (I) is the *in-phase* carrier and the other (Q) is the *quadrature* carrier.

The simplest form of quadrate modulation is to modulate each carrier independently by digital signals that shift the phase by 0 or 180°; then, combine the modulated carriers into one signal. **Figure 3** shows a typical *4-PSK* waveform with each carrier's phase being reversed by the digital signals and then added together to create four different possible phase shifts: 0°, 90°, 180°, and 270°.

Because there are two carriers — each being in one of two states (reversed or not reversed) — that creates four possible combinations. It is interesting to note that if the carriers are amplitude-modulated with signals of +1 and -1 (which is the same as a 180° phase shift), then the output signal for this QAM signal is exactly the same as for QPSK.

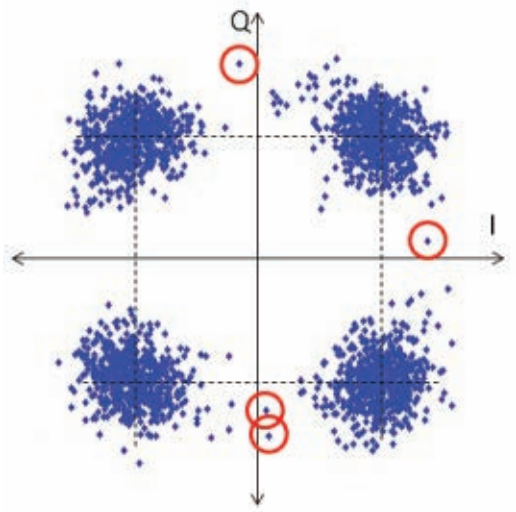
A number of amateur radio modes use QPSK. The popular VHF/UHF D-STAR system uses 4-PSK; there is a QPSK31 variation of PSK31; and there is a recently introduced digital voice mode suitable for use on the HF bands called FreeDV. Regulatory limitations on symbol rate and bandwidth have limited the data rate of digital modes on amateur radio in the US, but this is currently under evaluation by the FCC.

Tuning In to Digital Modes

You can get an idea of what these signals actually sound like from samples of signals that can be played back online. The ARRL's "Modes and Systems" web page (**www.arrl.org/modes-systems**) includes many explanatory articles in its "Digital Data Modes" section. Look for the link to "Digital Mode Samples."

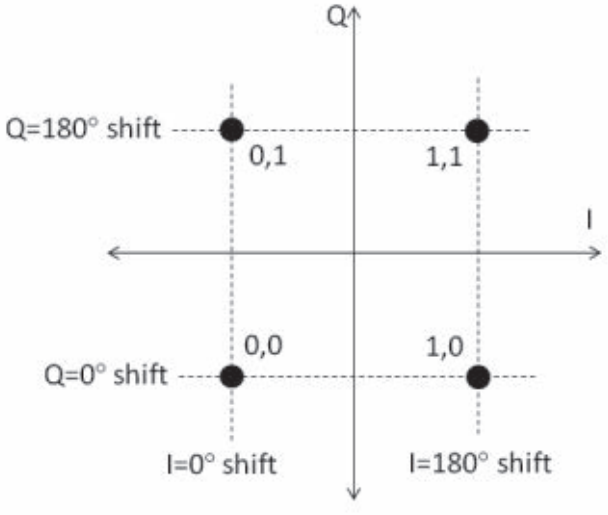
Another such website is on the HF Radio website at **hfradio.org.uk/html/digital_modes.html**. Click and enjoy!

If you have a general-coverage receiver and can hook it up to a PC, the popular Fldigi software package (**www.w1hkj.com/beginners.html**) is completely free and can decode more than 100 modes!



■ **FIGURE 4.** Alternate + Noise

Quadrature modulation is often described and measured by using a *constellation diagram*. **Figure 4A** shows a constellation diagram for the QPSK signal in **Figure 3**. Each of the two carriers (I and Q) has their own axis, along with their phase shifts (0 or 180°). The resulting four combinations are shown as dots. Depending on the digital data input to the two modulators for I and Q, the resulting modulated signal is described by one of



■ **FIGURE 4.** (A) Constellation diagram showing four states for QPSK; (B) shows the effects on the signal of adding noise and distortion.

those dots. The arrangement of dots — the constellation — depends on the number of phase and amplitude variations in the modulation scheme.

Figure 4B shows what happens when the real world starts adding noise, distortion, delay, and other disturbances to the modulated signal. The individual dots show actual values of the modulated signal for a large number of bits. Notice how what were once nice clean dots are spread and smeared. This makes the job of the receiving decoder a lot harder!

The red circles in the **figure** show some dots for which it might not be easy to decide what values are represented. For example, does the signal corresponding to the top circled dot represent 0,1 or 1,1? You can't tell from this diagram.

In order to combat uncertainty caused by noise, the first step taken was to add *error-detection* to the transmitted data. The *parity bit* is one such mechanism, indicating how many bits in a received sequence should be 1 or 0. If the result doesn't match, the data contains an error and the rules of the protocol decide what to do about it.

Another step was to add enough data for the receiver to correct some types of errors. This is called *forward error correction* or FEC. The extra bits slow down the transmission process, but overall, the time required for transferring error-free data is reduced.

Finally, the codes themselves were modified so that the receiving system could predict where the "next" bit's code would be in the constellation. This allowed the receiver to disregard some possible states and simplify the constellation. Simpler is better from the standpoint of errors. There are a number of these codes such as Gray, Hamming, Viterbi, and many more.

The Stop Bit

At some point, I have to stop writing about codes and modulations — this is that point! Digital communications is the standard today, even replacing the simple headphone jack on many of our audio gadgets. Amateur radio — once freed to experiment with and develop its own digital ways and means — has become a hotbed of mode and protocol experimentation.

Will digital sweep the dots and dashes of Morse from the airwaves? Don't count on it! Do count, however, on hearing a large number of other interesting signals on the ham bands. **NV**

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